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TRANSIENT COLOR PHENOMENA IN A DESERT

Prepared by

The Louis Comfort Tiffany Foundation

Oyster Bay, Long Island, N. Y.

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FOREWORD

During the summer of 1942, the Corps of Engineers (U. S. Army) was concerned with specifying camouflage materials for use in the impending battles on the African desert. When civilian artists attached to the Corps of Engineers were sent to study the camouflage requirements at camps in the desert country near Indio, California, it was reported that the standard camouflage materials often behaved in an unexpected manner when seen against desert landscapes, the camouflage measures being considered quite inadequate at certain times of the day.

Representatives of the Camouflage Section of the N.D.R.C. who conferred with the Army engineers concerning these "color transients" expressed the opinion that they are attributable to the normal color changes that occur as a consequence of gross variation in the quality of the illumination. At the time of these conversations, the Camouflage Section was arranging for the design and construction of an instrument which was later to be called a "spectrogeograph"; and it was expected that the use of this instrument would require field studies in the vicinity of the California desert. The Section therefore offered to make a study of color transients on the California desert; and the Army formalized its request for such a study under A/N Project Control No. CE-26.

The spectrogeograph expedition was organized in the spring of 1944, as soon as the spectrogeograph had been completed and given preliminary flight tests. The following report of the Tiffany Foundation sets forth the conclusions reached as a result of a study of these transient phenomena; conclusions that are in general agreement with the opinions that were expressed apriori. The report also includes recommendations with respect to procedures in the selection of camouflage materials that should result in reducing the transient effects to a minimum.

Cambridge, Massachusetts.
April 10, 1945.

Arthur C. Hardy,
Chief, NDRC Section 16.3.

I. PURPOSE

Personnel and equipment, which may have been successfully camouflaged for the most usual conditions in the desert, are nevertheless occasionally seen with vivid color contrast against a typical desert terrain. This contrast may appear at any time of the day, but it is most common when the sun is low, in the early morning or late afternoon. The effect is usually of short duration, at least in its most vivid phases.

The purpose of this investigation was to record the colors of camouflage materials and of typical desert terrains at various times of the day and for various natural conditions of lighting and observation in the desert. It was expected that an explanation of the nature of the transient color contrasts would be discovered upon correlating these data with carefully recorded descriptions of the transient contrasts.

II. CONCLUSIONS

As a result of measurement and careful observation of colors of various materials and typical desert terrains, at various times of the day and for various weather conditions, it is concluded that:

(1) The colors of camouflage materials and of their terrain backgrounds undergo great changes as the conditions of lighting and observation change in the desert.

(2) These changes are all caused by optical phenomena of generally recognized and well understood character.

(3) The changes of the color of the background terrain are either

not noticed or are severely underestimated by human observers, in a manner well known to psychologists and color photographers.

(4) The changes of color of camouflage materials are not recognized or are severely discounted as a consequence of the universal tendency to attribute a fixed color to any material, regardless of the color of the phase of daylight with which it may be illuminated.

(5) The changes of the colors can be of quite different kind for near-by objects than for distant backgrounds. Almost unnoticed changes of the individual colors can result in very apparent color contrasts. Such effects are much more likely to be noticed in the desert than elsewhere, because of the great distances which are commonly seen, and the clarity of the atmosphere which results in a very deep blue haze that causes the least possible interference with visibility but which does have important color effects.

(6) The mental conflict aroused by the appearance of an obvious color difference between an object and its background which were formerly matched and for each of which no color change has been noticed, is subconsciously resolved by the perception of a mysterious color component superimposed on only the near-by object. The visibility of the supposedly camouflaged object is then attributed to this mysterious added component.

(7) Distant scarf clouds, which may shadow distant terrains but be themselves invisible because hidden by the intervening blue haze, may produce lighting contrasts similar to those

of sunrise and twilight. The resulting color contrasts may be very striking because of their sudden appearance without any visible cause. The optics of this situation is similar to that occurring with a low sun and both colorimetric problems can be handled by the same general procedure.

(8) No single camouflage treatment can be expected to conceal near-by objects against distant backgrounds at all times of day and for all weather conditions in the desert. The camouflage, however, can be designed so that optimum concealment is afforded during the most critical hours and so that the extremes of color contrast occurring at other times are reduced to a minimum. Colorimetric procedures for the design of desert camouflage are proposed.

III. DISCUSSION

The color of daylight incident upon an object in the desert can vary from the yellowish-white of direct overhead sunlight; to the deep blue from the clear blue sky, which is the sole illumination of objects in the shade including the shadowed sides of mountains, hills and hillocks; to deep purplish-red at sunrise and sunset when the illumination from the blue sky is comparable in magnitude with the illumination from the low, darkened and very reddened sun; and can assume an infinite variety of other hues when the light reflected from large, bright, near-by features of the terrain contributes an appreciable fraction of the illumination. The colors by which objects are seen are the colors of the light reflected by them and depend upon the color of the illumination just as importantly as upon the colorant (pigment or dye) of the objects. Therefore, the colors of all objects in the desert change over a very wide range when the color of the illumination changes to the extents just described.

Human beings notice these color changes only in the most extreme cases. Even artists paint the vivid colors of the sunset sky without indicating more than the faintest suggestion of the resulting changes of the colors of near-by features of the landscape. This is a phenomenon of human vision that is well known to psychologists and photographers. Hundreds of scientific articles and dozens of weighty tomes have been written concerning this effect, which is called color constancy, color adaptation or color fatigue depending upon the observations or theoretical predelictions of the authors. This voluminous literature has little of practical value concerning either the quantitative specification of the magnitude of the effect or the underlying physiological processes, which are responsible for it. The fact alone is well established, qualitatively, and is best described by stating that human perception of color tends to compensate for changes of the color of the prevailing illumination, so that the colors of objects are sensed as approximately unchanged despite very great changes in the physical character of the reflected light. The color of daylight itself, or the average color of the entire surroundings of an observer, is also perceived almost as if it were unchanged throughout the day, and for various weather conditions. Except in the desert, or possibly also on snowfields or beaches of great expanse, these several varieties of the effect called "color constancy" are usually in the same direction for objects and their backgrounds, and anomalies or perceptual conflicts rarely

arise. In deserts, however, where the background terrain is frequently at a great distance from camouflaged objects, the blue haze intervening between the background and the camouflage may be, for low sun or some weather conditions, comparable in brightness with the brightness of the camouflage, and result in a very great difference of color between the camouflage and its haze-covered background. This color contrast is, of course, vividly apparent. This perception is, however, in conflict with the perceptions of the colors of the background and camouflage, since both of these are perceived almost as if unchanged from their appearance at noon. Because of this perceptual conflict the failure of erstwhile good camouflage is very commonly perceived as an extraneous color component superimposed on the camouflaged objects, rather than as differential changes of the colors of both the camouflage and its background. The constancy of the perceived colors of objects and of their illuminations is so persistent that it is not easily broken down even by such obvious anomalies as are observed in the desert, but the perceptual conflict is unconsciously resolved by the perception of a transient color component, sufficient to account for the obvious color difference, overlaying and "revealing" the near-by camouflaged objects.

Human inability to judge the color changes of natural daylight, or of the effects of these changes on the color of the light reflected by an object, is painfully familiar to color photographers. Their unpleasant familiarity with this fact is a consequence of the fact that color films record the color of the light without making any compensation for changes in the color of the prevailing illumination. When a near-by object is photographed in full daylight, with film manufactured for this condition, the appearance of the object is reproduced with satisfactory fidelity. If, however, the same object is photographed with the same film at sunset, the resulting picture will exhibit an overall reddish or purplish-red appearance that is a reproduction of the actual colors at least as accurate as the photograph made with full daylight, but which is regarded as unsatisfactory because the colors were not so perceived by the photographer. Likewise, when a distant landscape is photographed with the same film, especially near sunset, the resulting picture will exhibit an overall bluish cast, so much more pronounced than the haze perceived in the actual scene that it is usually condemned as false and unsatisfactory despite the fact that the actual colors are reproduced as accurately as in the most acceptable pictures made with the same film in full daylight. Dissatisfaction is felt with color photographs made in such circumstances because they fail to simulate the little known and poorly understood visual phenomena of color constancy. In the present instance, however, color photography records the facts, which account for color transients, that the colors of camouflage and distant terrains although identical at noon are all greatly changed near sunset and changed differently so that the camouflage obviously ceases to blend with distant backgrounds.

The perception of color transients as color components additional to the colors of objects is an illusion, but the observed color differences are real and are caused by natural and well understood conditions of lighting and observation. The subject need not be confused by consideration of mysterious factors such as are implied by some descriptions of the perceived color transients.

It is an inescapable fact that real color differences are certain to occur at some times of the day and states of the weather, between a distant background and any near-by object, no matter how it is camouflaged. Possibilities for improvement seem to be confined to selection of the phase of daylight for which the camouflage would most advantageously be perfect. This decision involves several considerations. First, the color difference should be negligibly small for the most probable conditions of illumination and observation at the most critically important hours of the day. Second, the greatest color differences which occur at any time can be and should be minimized by adjustment of the camouflage so that it is perfect for some conditions intermediate between the extreme conditions. Thus, although the camouflage may not be perfect at midday, it should not be seriously mismatched with its background either at midday or sunset, on either clear or overcast days. In this sense, it should be possible to use "color transients" to some extent for camouflage, if their origin and essential nature is thoroughly understood and exploited.

No unexpected measurable phenomena were recorded in this investigation, and since the experimental procedures were not designed to yield data useful for design purposes, no numerical results have been included in this report. It is suggested that existing data on the spectral distributions of various phases of daylight (refs. 1,2), of blue sky (which may also be used as the maximum blue haze), and on color discrimination (refs. 3,4) should be used in conjunction with standard methods (refs. 5,6,7) of colorimetric computation for the study and tentative design of desert camouflage.

Extreme cases, the consideration of which would probably give valuable indications of the performance of camouflage are: (1) contrast of the camouflage illuminated by the blue sky, viewed against a near-by (hazeless) background (sand, etc.) illuminated by complete daylight; (2) contrast of the camouflage in direct noon sunlight, viewed against a near-by background similarly illuminated; (3) contrast of the camouflage illuminated solely by the blue sky, viewed against blue haze (equivalent to blue sky) in front of a shadowed terrain; (4) contrast of the camouflage illuminated with direct sunlight, viewed against blue haze; and (5) contrast of the camouflage illuminated by "red" sunset light, viewed against blue haze. All except possibly case two correspond to circumstances in which transients could be observed. Less extreme cases can be approximated by interpolation between the results for color discrimination (or acuity) in the most directly related extreme cases. Compromises between the extreme cases will call for consideration of the relative operational importance of the several circumstances.

Examination of the results of computations such as outlined above will convey a clear understanding of the origin and nature of the phenomena responsible for the perception of color transients. Thus, for example, the point (A) in Figure 1 represents in the standard colorimetric manner the average color of an expanse of barren earth in full noon sunlight. The point (A) also represents the color of a camouflaged object which blends perfectly with the near-by background in full noon sunlight. Point (B) represents the color of the same kind of terrain, in full sunlight but at a distance of about five miles when the brightness of the intervening blue haze is ten per cent of the brightness of the terrain.

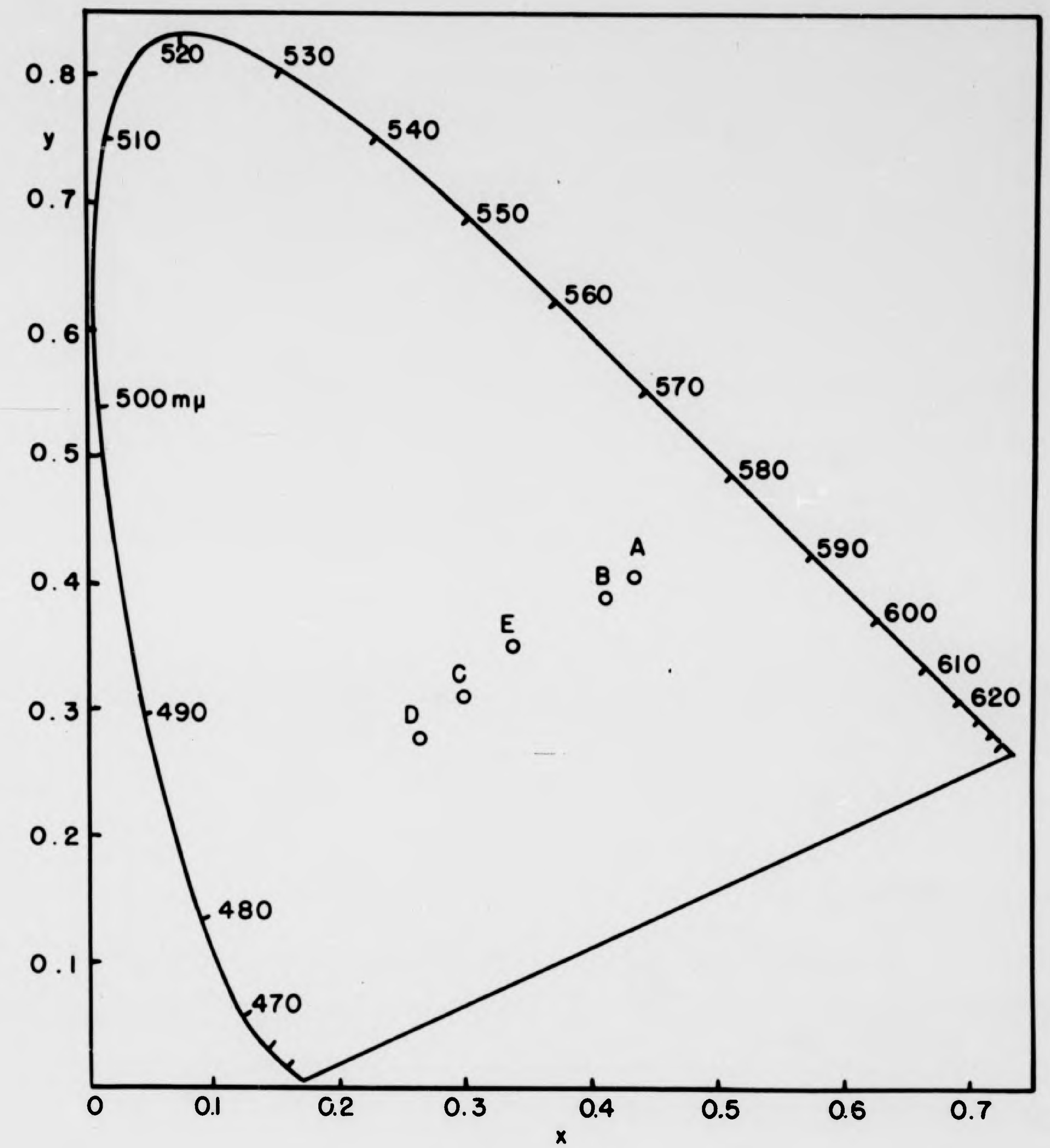

Figure 1 - Standard ICI chromaticity diagram, showing the variation of color of a selected terrain, near-by (A) and distant (B) in full noon sunlight, and shaded at a distance (C). A near-by camouflaged object which would blend against (A) would not blend against (B) or (C). The point (D) represents the color of blue haze which is combined in varying proportions with the "near-by" colors of all distant objects. The point (E) represents the color of direct noon sunlight.

The effect of the haze on the color of the background is not ordinarily perceived, but the color difference (A) - (B) between the near-by camouflaged object and its distant background is noticeable. Point (C) represents the color of the terrain at five miles when shadowed by an incline or scarf clouds so that the intervening blue haze is just as bright as the terrain. Even in this case, the change of color of the composite background (earth and haze) is not likely to be noticed, but the color contrast of near-by camouflage (A) against the background (C) is enormous. Since the explanation of the contrast is naturally sought in the camouflage a fictitious yellow color transient would probably be perceived on the camouflage. In reality, the color of the camouflage is unchanged and there is merely a perfectly natural, although almost unnoticed, change (towards blue) of the color of the background. For this example, the color of blue haze (D) has been assumed to be that of Taylor and Kerr's zenith sky (ref. 1), and the effects of haze have been approximated as simple additive mixtures, without selective attenuation of the light from the distant terrain. In the third case (C) the color of the terrain (apart from the haze) was computed on the basis of illumination by zenith sky light. Point (E) represents the color of direct sunlight.

Table I, which is copied from the report of the Colorimetry Committee of the Optical Society of America, gives the wavelengths for selected ordinate calculations involving five phases of natural daylight. "Red" sunset illumination can be approximated by some low temperature "black body" illuminant. Selected ordinates for such sources, with temperatures of 2000°, 2500° and 3000° K are given in Table II. Similar data at intervals of 100° from

Table I

Selected Ordinates for Five Phases of Natural Daylight

Ordinate Number	Direct Sunlight (X)	Direct Sunlight (Y)	Direct Sunlight (Z)	Sun plus Sky Horizontal Plane In Cleveland, Ohio (X)	Sun plus Sky Horizontal Plane In Cleveland, Ohio (Y)	Sun plus Sky Horizontal Plane In Cleveland, Ohio (Z)	Overcast Sky (X)	Overcast Sky (Y)	Overcast Sky (Z)
1	427.1	471.7	413.8	425.1	468.6	413.6	424.4	467.6	413.8
2	440.6	493.6	422.4	437.6	491.2	422.0	435.9	490.0	421.8
3	451.7	504.7	426.6	447.5	502.8	426.2	445.3	501.7	425.9
4	463.7	512.3	429.7	457.3	510.7	429.2	454.7	509.2	429.1
5	489.0	518.4	432.4	468.9	516.4	431.9	464.6	515.0	431.6
6	538.3	523.4	435.0	524.6	521.2	434.5	483.0	520.1	433.9
7	548.1	527.9	437.5	541.7	525.9	437.0	536.2	524.4	436.2
8	555.2	532.0	439.8	550.3	530.1	439.2	546.8	528.6	438.4
9	561.2	535.8	441.9	556.9	534.0	441.3	554.4	532.5	440.6
10	566.3	539.5	443.9	562.5	537.8	443.4	560.8	536.3	442.7
11	570.8	543.0	445.9	567.5	541.5	445.4	565.8	540.0	444.8
12	574.9	546.5	448.0	572.0	545.0	447.4	570.7	543.5	446.9
13	578.7	549.9	450.0	576.1	548.5	449.3	574.8	547.0	448.9
14	582.3	553.3	452.0	580.0	551.9	451.3	578.9	550.5	451.0
15	585.8	556.7	454.1	583.7	555.3	453.3	582.8	554.0	453.0
16	589.3	560.2	456.1	587.3	558.7	455.2	586.5	557.5	455.0
17	592.7	563.7	458.0	590.8	562.2	457.2	590.1	561.0	457.0
18	596.0	567.3	459.9	594.2	565.7	459.1	593.6	564.6	458.9
19	599.3	570.9	461.9	597.7	569.4	461.0	597.1	568.3	460.8
20	602.6	574.6	463.9	601.1	573.2	463.0	600.6	572.1	462.8
21	605.9	578.5	466.1	604.6	577.1	465.1	604.2	576.1	465.0
22	609.4	582.6	468.4	608.2	581.1	467.4	607.9	580.3	467.3
23	612.9	587.0	470.8	611.9	585.5	469.8	611.7	584.8	469.7
24	616.6	591.7	473.4	615.7	590.3	472.4	615.8	589.6	472.3
25	620.7	596.8	476.4	619.8	595.5	475.3	620.2	594.9	475.2
26	625.4	602.4	480.1	624.5	601.4	478.8	625.0	600.7	478.5
27	630.7	609.1	484.2	629.8	608.1	483.0	630.6	607.7	482.9
28	637.4	617.1	489.5	636.5	616.1	488.2	637.5	616.1	488.0
29	646.6	627.8	498.3	645.7	627.0	496.9	646.5	627.4	496.7
30	664.3	647.8	514.9	663.3	646.8	513.3	663.9	647.8	513.0
Factor	.03200	.03333	.02985	.03199	.03333	.03424	.03190	.03333	.03655

Table I (Continued)

Selected Ordinates for Five Phases of Natural Daylight

Ordinate Number	North Sky Light on 45° Plane (X)	(Y)	(Z)	Zenith Sky (X)	(Y)	(Z)
1	417.8	462.3	411.8	418.8	459.9	410.8
2	430.5	484.1	420.2	430.1	482.0	419.7
3	438.2	496.1	424.4	435.8	494.3	424.0
4	445.1	504.5	427.7	441.4	503.0	427.5
5	451.8	510.7	430.2	447.2	509.3	430.0
6	458.8	515.8	432.6	452.8	514.4	432.4
7	466.5	520.5	435.0	459.3	518.9	434.8
8	479.5	524.5	437.3	466.3	523.0	437.0
9	533.3	528.4	439.5	477.6	526.8	439.0
10	544.7	532.1	441.7	531.4	530.4	440.9
11	552.5	535.7	443.8	543.3	533.9	442.8
12	558.7	539.2	445.9	551.2	537.3	444.8
13	564.3	542.6	447.9	557.9	540.7	446.7
14	569.3	546.1	449.9	563.5	544.1	448.6
15	573.8	549.5	451.9	568.7	547.5	450.5
16	578.1	552.9	453.8	573.3	550.9	452.4
17	582.2	556.4	455.8	577.8	554.3	454.3
18	586.2	560.0	457.7	582.1	557.8	456.3
19	590.1	563.6	459.6	586.3	561.4	458.3
20	593.9	567.3	461.5	590.3	565.2	460.3
21	597.8	571.2	463.5	594.3	569.1	462.4
22	601.7	575.4	465.7	598.4	573.2	464.5
23	605.8	579.8	468.1	602.6	577.6	466.9
24	610.0	584.5	470.6	606.9	582.3	469.5
25	614.5	589.8	473.4	611.5	587.4	472.3
26	619.5	595.3	476.7	616.6	593.3	475.5
27	625.0	602.6	480.9	622.2	600.0	479.5
28	631.8	610.9	486.0	629.0	608.4	484.7
29	641.2	622.2	494.2	638.9	619.6	492.7
30	658.9	642.3	510.3	656.2	639.7	508.6
Factor	.03151	.03333	.04879	.03156	.03333	.05506

Table II

Selected Ordinates for Tristimulus Values with Black Body Illuminants

2000° (X)	(Y)	(Z)	2500° (X)	(Y)	(Z)	3000° (X)	(Y)	(Z)
518.8	500.3	420.8	452.4	492.1	417.7	440.9	486.0	415.8
549.5	518.0	428.9	536.1	511.2	426.3	475.3	506.4	424.6
560.1	527.3	433.8	550.7	520.5	430.8	540.4	516.0	429.1
567.5	534.3	437.7	559.6	527.3	434.5	551.7	522.9	432.5
573.1	540.2	441.0	565.9	533.1	437.6	559.1	528.5	435.4
577.8	545.4	444.0	571.2	538.2	440.4	565.2	533.5	438.1
582.2	550.2	446.7	575.8	542.9	443.1	570.3	538.0	440.6
585.9	554.6	449.4	579.9	547.3	445.5	574.8	542.3	443.0
589.4	558.8	451.9	583.8	551.4	447.9	578.8	546.4	445.3
592.7	562.8	454.2	587.2	555.3	450.3	582.5	550.2	447.6
595.8	566.5	456.5	590.4	559.0	452.5	585.9	554.0	449.8
598.7	570.2	458.7	593.4	562.7	454.6	589.2	557.7	451.9
601.6	573.8	460.8	596.5	566.3	456.8	592.2	561.3	454.1
604.3	577.4	462.9	599.4	569.9	458.8	595.5	564.9	456.1
607.1	580.8	465.0	602.2	573.4	460.8	598.4	568.4	458.1
609.8	584.3	467.0	605.0	577.0	462.8	601.2	571.9	460.1
612.5	587.8	469.2	607.9	580.5	465.0	604.1	575.5	462.2
615.2	591.4	471.4	600.6	584.1	467.1	607.1	579.1	464.3
618.0	595.0	473.6	613.4	587.8	469.3	610.0	582.7	466.4
620.8	598.7	476.1	616.3	591.5	471.5	612.9	586.5	468.5
623.7	602.5	478.7	619.3	595.4	473.8	615.9	590.4	470.8
626.8	606.4	481.4	622.4	599.4	476.3	619.0	594.5	473.3
630.1	610.6	484.6	625.6	603.6	479.4	622.4	598.8	476.1
633.7	615.0	488.0	629.2	608.2	482.5	626.0	603.4	479.1
637.6	619.8	492.0	633.1	613.1	486.1	629.9	608.4	482.5
642.0	625.1	496.7	637.6	618.6	490.5	634.4	614.0	486.6
647.1	631.2	502.1	642.7	624.8	495.7	639.6	620.3	491.7
653.7	638.8	509.0	649.3	632.4	502.4	646.0	628.0	498.1
662.7	649.1	518.7	658.2	642.9	511.5	655.0	638.6	507.2
681.1	668.2	538.5	676.1	662.2	530.5	672.5	657.9	525.2

Factors =

2000° (X)	(Y)	(Z)	2500° (X)	(Y)	(Z)	3000° (X)	(Y)	(Z)
1.273	1.000	0.1458	1.152	1.000	0.2656	1.080	1.000	0.3945

2000° to 4000° K are tabulated in the report of the Colorimetry Committee of the Optical Society of America, in which the use of such data is explained with examples.

In addition to clarifying the problems of desert camouflage, a systematic but not necessarily long series of computations of the kind outlined above would be a valuable preparation and guide for field experiments. Camouflage colors chosen on the basis of actual field tests, with compromises between the conflicting requirements based on an understanding of the phenomena which would be induced by study of a few such computations, are much more likely to be successful than any which might be chosen by computations alone, even if ideally complete fundamental data could be obtained. The mere elimination of the mystery of color transients, which is the easiest result of such computations, should prove a tremendous advantage to those responsible for observing and evaluating camouflage colors.

IV. DESCRIPTION OF EXPERIMENTS

Changes of Natural Illumination

A set of nine panels was constructed in typical open desert in the Coachella Valley, California. The co-operation of the Thermal Test Branch of the Engineer Board, and the courtesy of the Acting Chief, Lt. R. R. Stander, are gratefully acknowledged. Mr. Graham of the Engineer Board, Fort Belvoir, Virginia, furnished invaluable assistance. The panels consisted of a white reference standard, for determination of the color of the illumination, and eight chromatic panels. The colors of these panels were measured with an Eastman Universal Colorimeter throughout

several days, with various weather conditions. Camouflage materials of all standard colors were also measured at close range. A camouflage net was measured from a distance just sufficient to obtain an average color by throwing the colorimeter slightly out of focus. The colors of the panels and of the camouflage materials when observed under various conditions of weather and at various altitudes of the sun were all quite similar to those which could be predicted for the several different phases of daylight by use of the standard methods of colorimetric computation. All observed changes were attributable directly to the differences of the corresponding colors of the illumination, even at times when color transients were clearly perceived.

The colors of near and distant sand banks and vegetation were also recorded by the use of an Eastman Universal Colorimeter. Such observations were repeated at various times of the day and for various weather conditions. All of these colors could be accounted for directly on the basis of the corresponding colors of the illumination and the assumption of an appropriate intensity of blue haze and atmospheric attenuation.

V. DESCRIPTION OF THE EASTMAN UNIVERSAL COLORIMETER

An Eastman Universal Colorimeter was used in this investigation because it is independent of laboratory facilities, easily portable, and sufficiently simple in operation for field use. This type of instrument was originally designed and built in 1918 under the direction of the U. S. Navy for use on shipboard. The original purpose was to facilitate the study and recording of the colors of the horizon sky under various conditions of weather, throughout the regions in which vessels were subject to attack by submarines. These data were required for the design of marine camouflage. A shipboard photometer was also designed for the measurement of the brightness of the horizon sky. Naval crews were trained in the use of these instruments. Plate I is a picture taken during the training period. These instruments were used on several voyages in the North Atlantic during 1918.

The Eastman Universal Colorimeter appears in the center of Plate I. The electrical controls for the internal light source are located in the box under the tripod of the colorimeter. This is the only accessory apparatus necessary for use with the colorimeter. The carrying case for the colorimeter may be seen beneath the control box.

Plate I - Eastman Universal Colorimeter

Following World War I, this colorimeter was manufactured and distributed by the Eastman Kodak Company, for general industrial and scientific use. One of these commercial instruments was used in the present investigation. Several accessories were designed for the measurement of the color of transparent and reflecting materials, in addition to the original function of measuring the color of light and distant targets. The use of this type of instrument has almost ceased of recent years as a result of the development of successful photoelectric recording spectrophotometers. Since the great majority of industrial color measurements are concerned with reflecting and transmitting materials, indirect colorimetry, based on data furnished by accurate spectrophotometers is sufficient and less subject to personal error than any method of direct colorimetry.

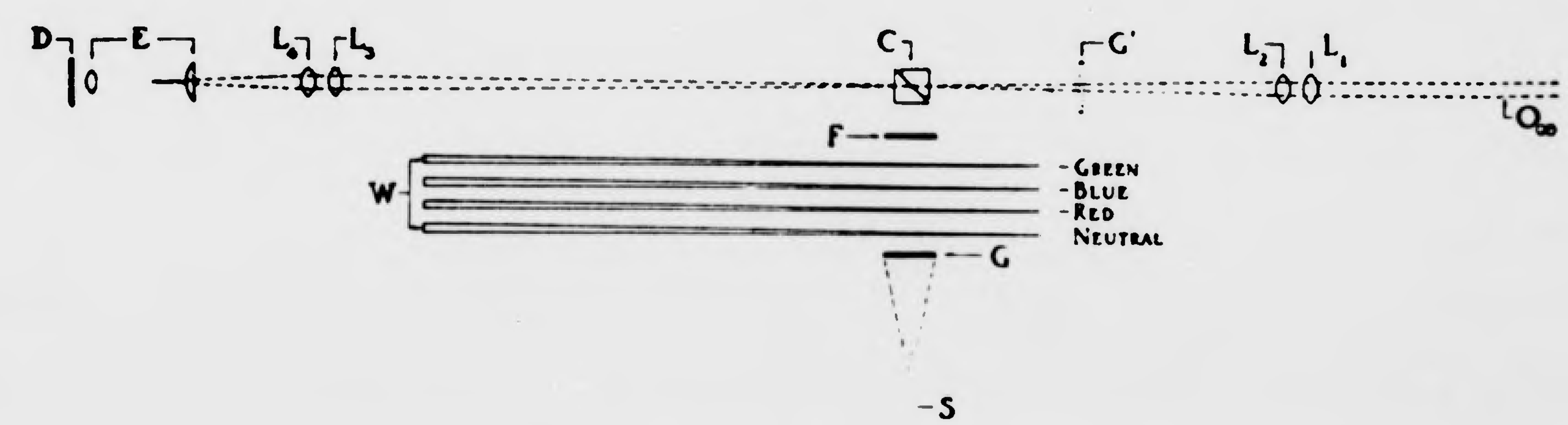

Figure 2 - Optical diagram of an Eastman Universal Colorimeter. The distant target whose color is being measured is indicated off to the right, by (O_∞). The lenses (L_1) and (L_2) serve to focus an image of the target in the center of the photometric cube (C). The lenses (L_3), (L_4), and (E) form an eyepiece by which the observer examines the colors in the cube (C). Light from an internal source (S) is diffused by a ground glass plate (G) and is passed through the four wedges (W), the positions of which are adjusted to produce a color matching that of the distant target. Auxiliary filters may be inserted at (F) or (G') whenever the target is very much brighter or darker than the internal source. The diaphragm (D) is part of the eyepiece and has a small hole which serves as an artificial pupil.

Direct methods of colorimetry are almost indispensable, however, for measurement of the color of light from self-luminous sources and from distant objects, especially when the contribution of the intervening haze and the effects of the varying quality of the illumination are of interest. Since the colors involved in the transient contrasts seen in the desert fall within this class, direct colorimetry was necessary and the Eastman Universal Colorimeter seemed particularly well suited for this investigation.

The Eastman Universal Colorimeter consists of a telescope which focuses an image of a distant target in one portion of the field of a photometric cube, Figure 2. The comparison portion of the field of this photometric cube is illuminated by a light source contained in the colorimeter. This light source is operated at a constant color-temperature by use of a voltage control box. This box contains batteries, an adjustable resistor and a voltmeter so that the voltage of the lamp may be set to prescribed values. The light from the lamp is transmitted by four dyed gelatine wedges, which serve to modify the color and intensity of the light reaching the photometric cube from the comparison source. Each of these wedges is on a long, narrow glass strip. The thickness of the dyed gelatine on each of these strips varies from zero near one end of the strip to a maximum thickness near the opposite end. One of these wedges absorbs primarily the red region of the invisible spectrum. The appearance of this wedge is bluish-green, but in accordance with its function (absorbing red light) this wedge is known as the "minus-red" wedge. The primary function of the second wedge is to absorb blue light. This filter has a yellow appearance but, in accordance with its function, is known as the

"minus-blue" wedge. The third wedge absorbs green light most strongly. The appearance of this wedge is pink, but it is known as the "minus-green" wedge. The fourth wedge is relatively nonselective in its absorption and serves to decrease the brightness of the synthesized color with very little effect on the color. The portion of each of these wedges which is placed in the path of the light from the comparison source may be varied by sliding the wedge in a track which passes beneath the photometric cube. Each wedge is provided with a handle and an indicator. Four fixed scales of distance are placed on the outer frame of the colorimeter. The positions of the wedges are marked on these scales by the indicators and when the two halves of the photometric cube are matched, these readings may be taken as specifications of the color of the light from the distant source. The interpretation of the data is simplified by the rule that not more than two of the three colored wedges are to be used in matching any color. The neutral gray wedge may be used in order to make the brightness of the comparison field match that produced in the photometric field by the distant target. Two neutral filters are provided which may be placed in the telescope to reduce the intensity of the light from the distant source.

VI. CALIBRATION OF THE EASTMAN UNIVERSAL COLORIMETER

The chief limitation of the Eastman Universal Colorimeter was the lack of a calibration in standard colorimetric units. The standard method of colorimetric specification was adopted in 1931 by the International Commission on Illumination, meeting in Cambridge, England. This method has since been applied to almost every procedure for the measurement of color. The use of this system of specification was recommended by the American Standards Association, as an emergency War Standard, Z 44. The calibration of the Eastman Universal Colorimeter in terms of this standard was, therefore, considered desirable. By use of such a calibration the results obtained with the Eastman Universal Colorimeter could be expressed in the standard terms for comparison with other data and in order to take advantage of familiarity with the behavior of ordinary colors in natural daylight.

As ordinarily used, the indications of the scales of the Eastman Universal Colorimeter are adequate for the specification of color. In order to match a color, which is the usual industrial problem, it is merely necessary to prepare a sample which gives the same settings of the wedges. The fact that the wedge scales are arbitrary and the absolute calibration unknown is of no disadvantage in such problems. However, for comparison of the data with results obtained by other methods it is necessary to have some means of converting the readings to the generally recognized system of color specification.

A conversion network was first devised for the purpose of determining approximate ICI color specifications directly from the readings obtained with the Eastman Universal Colorimeter. Corrections of the values obtained in this way are necessary, however, corresponding to the various settings of the neutral wedge and when the auxiliary neutral filters are used. Uncertainties in these corrections, and in the conversion network itself led to the abandonment of this method of calibration, although it is potentially the most useful and convenient.

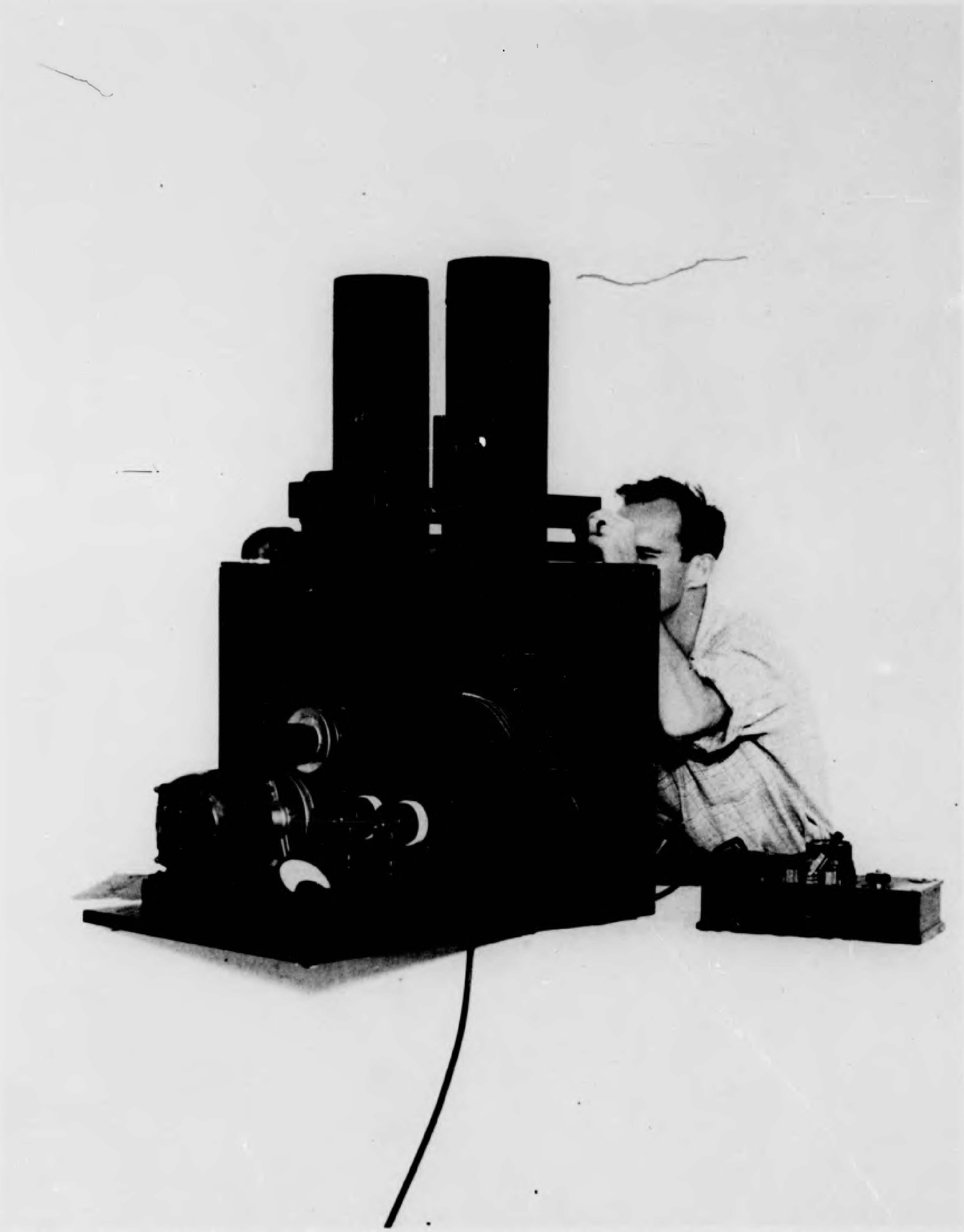

Plate II - Calibration Arrangement for Eastman Universal Colorimeter

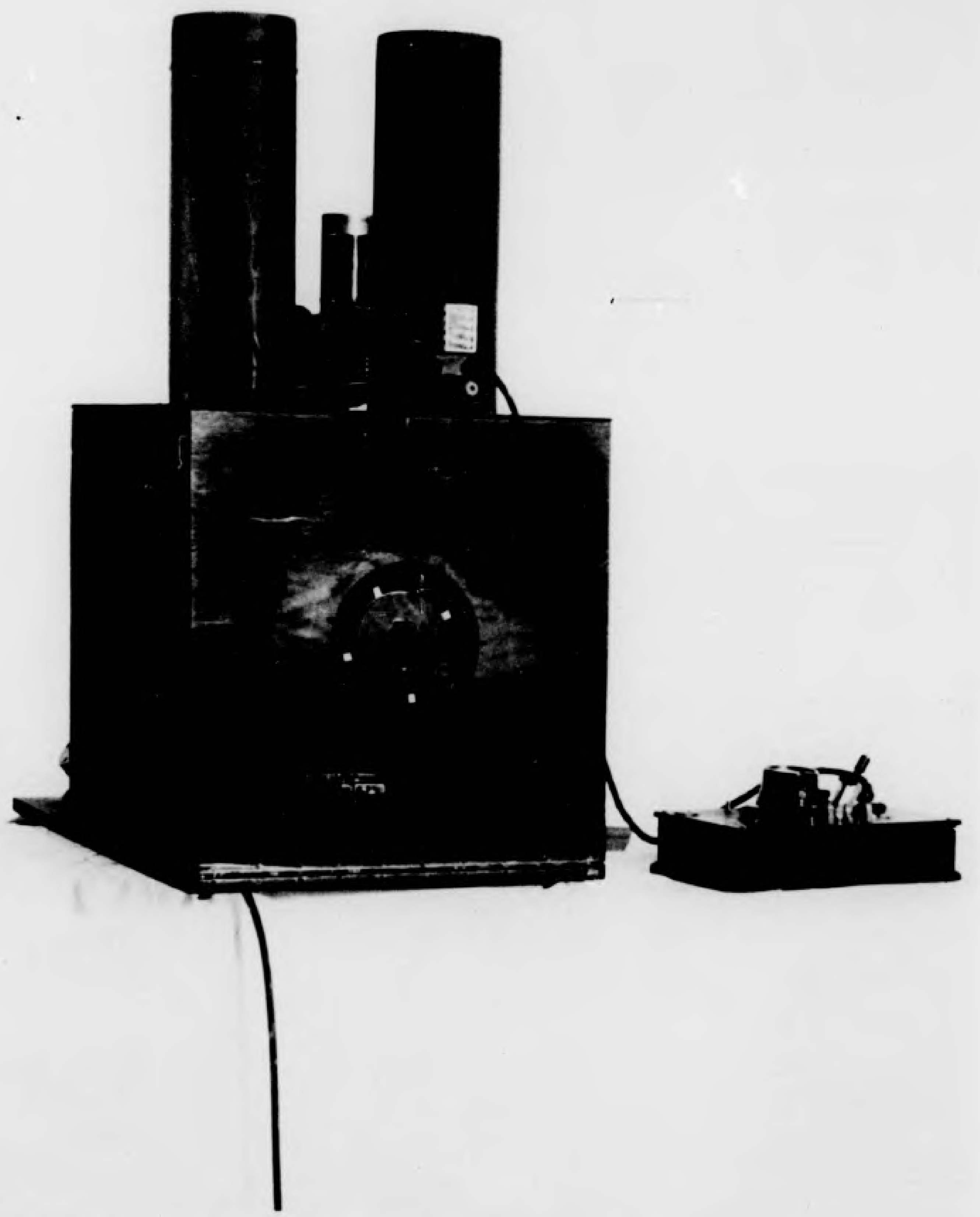

Plate III - Calibration Arrangement showing Colorimeter Eyepiece and Sector Disk Controls

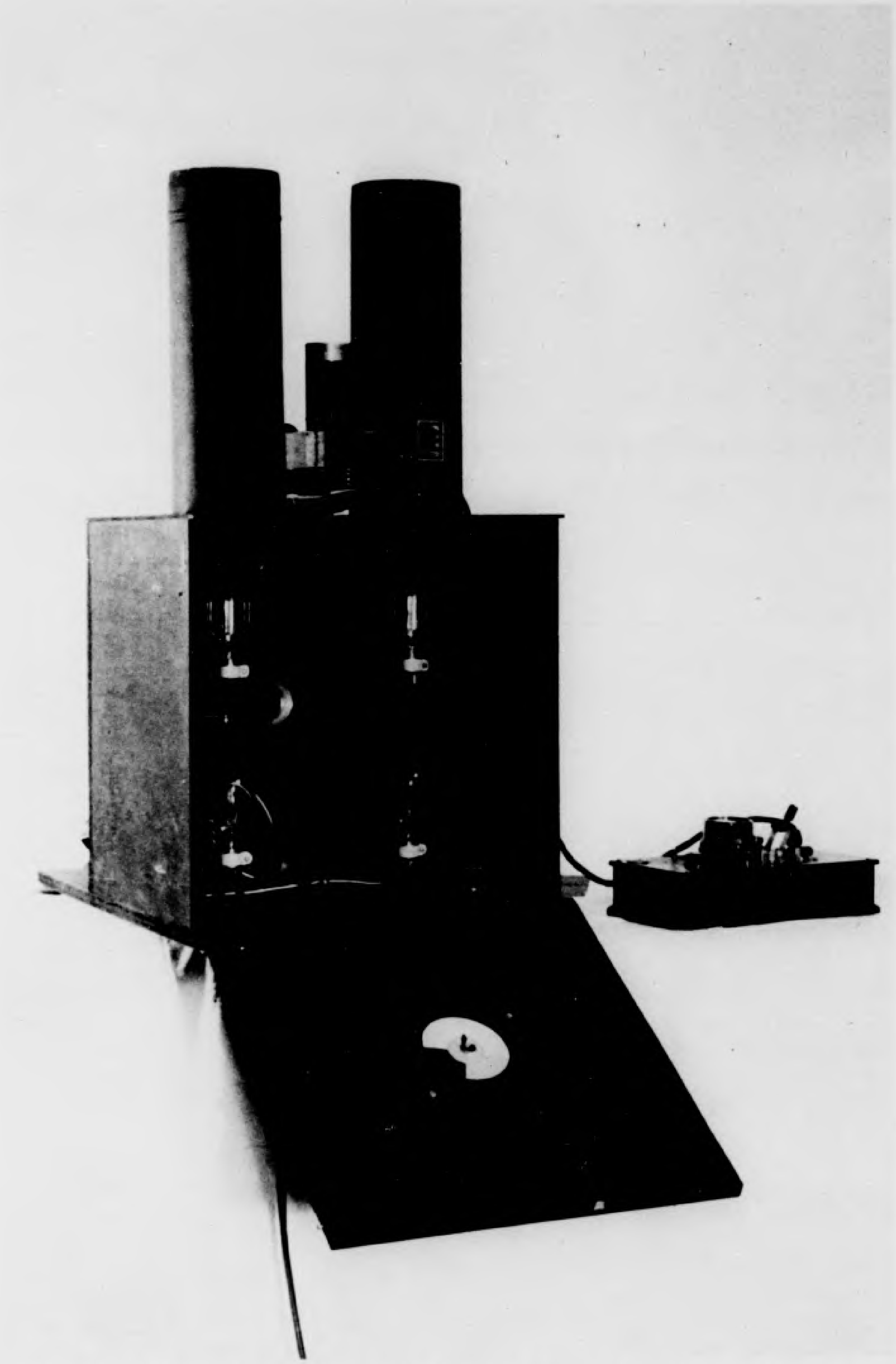

Plate IV - Interior of Calibration Device, showing Sector Disk and Lamps

The colorimetric specifications corresponding to the readings on the colors observed in the desert were finally determined by a method more direct and less dependent upon interpolation than the method just suggested. A disk colorimeter was constructed for this purpose. Several views of the calibration arrangement are shown in Plates II, III and IV. Plate II shows the operator at his station, the motor and pulley arrangement which produces a rapid scanning of the surface of a disk covered with differently colored sectors, and a periscope-like tube which puts the light from the sector disk into the Eastman colorimeter, which is mounted on top of the calibration device. Plate III shows the eyepiece and wedge case of the Eastman colorimeter and the external controls for the angles of the colored sectors. Plate IV shows the stationary disk which is covered with sectors consisting of Munsell papers, which could be changed and selected suitably for each color range. This disk was illuminated by the large lamps which can also be seen in Plate IV. These lamps were operated at a voltage such that their color temperature was 2848°K. The filter specified by the International Commission on Illumination for the production of Standard illuminant C was inserted between the sector disk and the deviating prism in the calibration device. Standard illuminant C was used because the colorimetric specifications of the Munsell papers were available for this illuminant. The side of the box ordinarily nearest the operator is open in Plate IV, showing how conveniently located are all the parts of the device which require frequent adjustment. A glass deviating wedge was rotated rapidly in the hollow shaft of the upper pulley seen in Plate II. After passing through this wedge, the light from the sector disk is reflected up through the

periscope tube (also shown in Plate II) and into the objective lens of the Eastman colorimeter. Consequently, the field of the Eastman colorimeter was filled in rapid succession with light from the three differently colored sectors of the disk. The rotation of the deviating prism, and consequently the rate of scanning the sector disk, was so rapid that there was no perceptible flicker of color. The blended color could be varied by varying the angular sizes of the sectors of the component Munsell papers. The ICI colorimetric specification of the resultant blended color could be calculated very simply from the known ICI specifications of the component disk colors and from the angular sectors used. The specific readings of the Eastman Universal Colorimeter were converted to ICI specifications in the following manner. The wedges of the subtractive colorimeter were set to the values recorded in the desert. The lamps of the Eastman colorimeter and of the disk colorimeter were operated at their specified voltages. The angles of the sectors of the papers in the disk colorimeter were varied until a perfect color match was obtained.

The location of the neutral wedge of the Eastman colorimeter was varied from the setting recorded in the desert in order to produce a brightness match. The same auxiliary "neutral" filter as was employed in the telescope during the measurements in the desert was also employed during the calibration readings in as many cases as possible. It was not possible to obtain as high brightnesses in the disk colorimeter as in the desert. Consequently, it was not always possible to obtain a match with the same neutral filter in the telescope. Corrections of the wedge settings were necessary to compensate for the use of a different filter.

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